Sweet sorghum: agronomic practice for food, animal feed and fuel production in sub-Saharan Africa

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SWEET SORGHUM: AGRONOMIC PRACTICE FOR FOOD, ANIMAL FEED AND FUEL PRODUCTION IN SUB-SAHARAN AFRICA

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ABSTRACT

Sweet sorghum is a cereal that belongs to the species *Sorghum bicolor (L) Moench*. Although the crop is reportedly native to Africa, it is grown worldwide largely because it thrives well under wide rainfall regimes, varied day lengths, soil conditions and can tolerate varying degrees of biotic and abiotic factors and stresses. This chapter reviews and discusses the physiology and adaptation of sweet sorghum crops to varied environmental and climatic conditions across Sub-Saharan Africa. Several research works have indicated that numerous improved cultivar types of sweet sorghum are grown across Africa. Virtually all sweet sorghum cultivars are primarily grown to produce grain, sugary stalk juice and forage or fodder. The grains are considered the 3rd most important source of staple food to people living in the Sub-Saharan Africa region. Furthermore, the grains may also be malted to produce beverages or utilized as adjunct in beer brewing. However, the sugary stalk juice is most commonly used for sorghum molasses or syrup production. Sorghum molasses or syrup is a suitable alternative to refined cane sugars in beverage consumption; particularly for diabetic patients. Thus, the nutritional value, health benefits and future prospects of sorghum grain consumption to address certain human health challenges are discussed in this chapter. Alternatively, the sugary stalk juice from sorghum may be bio-converted to bioethanol (a fuel alcohol). Sweet sorghum crop residues (i.e. leftovers and after the grains are harvested and stalk juice extracted) can serve as animal feed or utilized as lignocellulosic biomass for second generation bioethanol production. This chapter reviews and discusses literature that demonstrates sweet sorghum is a cereal crop with high tolerance to diverse environmental and climatic conditions. In addition, the crop produces nutritious grains and sugary stalk juice that are of important health and economic benefits for domestic and industrial applications throughout in Africa.

Keywords: Sorghum, Agronomy, Food, Fodder, Bioethanol, Health, Disease

INTRODUCTION

Sub-Saharan Africa refers to areas geographically located south of the Sahara comprising 48 countries [1,2]. An estimated 1 billion people reside~~s~~ across this region and this accounts for over 80% of the total African continent population [2]. Sub-Saharan Africa constitutes an estimated 43% of the arid and semi-arid land worldwide. Consequently, food production in the region is largely limited by water availability and infrastructural impediments [1,3]. In fact, about 90% of total agricultural land use is rain-fed dependent [3]. Therefore, for centuries local farmers were constrained to only selecting and cultivating crop varieties that are water use efficient, can tolerate and thrive well under their local environmental conditions and fit into their food preferences. For example, centuries of careful observation and planting trials has lead to the selection and adoption of varied sorghum cultivars with distinct qualities as food crops in Africa [4,5]. These sorghum cultivars range into thousands of varieties, depending on social, environmental factors and agronomic practice [4].

Although sorghum is reportedly indigenous to Africa, it is now grown worldwide for various industrial and domestic end-use applications. Studies have shown Sorghum crops (*Sorghum bicolor (L.) Moench*) exhibit wide ranges of adaptation capacity. The crop can be grown on land ranging from sea level up to 3000 meters altitude. This crop can tolerate varied day length, soil conditions, rainfall regimes (300mm - 1800mm precipitation) and a number of other biotic and abiotic factors stress [4,6]. Nevertheless, various research efforts in different parts of the world have been ongoing to improve the sorghum crop adaptability and stability for better yield. Consequently, a widely adapted and stable high grain and stalk sugar yielding sweet sorghum varieties are being developed and widely grown [7]. In Sub-Saharan Africa, sorghum grain is the second most important cereal after maize, this largely due to its relative ease for cultivation, adaptation to local conditions and nutritional value [8]. For example, sweet sorghum varieties are grown as multi-purpose crops; the grains are a staple food source while the sugary stalk juice are converted to syrup and the green residue serves as livestock feed [9]. Besides sorghum grain being an important staple source to rural populace, it has some industrial scale applications such as in malt drinks production and beer brewing. In addition, the sugary stalk juice is used to produce syrup, which serves as sweetener in beverages [7]. On a commercial scale, sweet sorghum stalk juice is widely considered a sustainable feedstock for bioethanol production [8]. Sorghum crop green residue (after grain harvest and/or stalk juice extraction) is typically utilised as animal feed or used in roof thatching and fencing in some rural areas in Africa. Though sorghum cultivars grown around the world are in the thousand varieties, the crop may be broadly classified as Grain, Forage and Sweet sorghums respectively [10]. Briefly, while Grain sorghum (as the name suggests) is primarily cultivated for grain production, the Forage sorghum is essentially grown for silage production (i.e. livestock feed) and sweet sorghum is grown for both sugary stalk juice and grain yield.

It is expedient to mention both Forage, Grain and Sweet sorghum cultivars produce grain. However, the grain sorghum cultivars produce the most quantitative and likely qualitative grains when compared to the Forage and Sweet sorghum cultivars in general [6]. The Forage sorghum in general produces more non-grain biomass than Grain sorghum and grows taller and thicker stalks. However, the Sweet sorghum cultivars produce sugary stalk juice that neither Forage nor Grain sorghum produces. Generally, the agronomic practice and cultivation management for all three cultivar types of sorghum discussed in this context are closely related or similar and their agronomic characteristics are same as well [4,5].

SWEET SORGHUM ORIGIN AND DOMESTICATION

Increased demand for food spurred by rapid population explosion in Sub-Saharan Africa and coupled with the need to develop a sustainable energy source has led to renewed interest for the development and cultivation of improved dual-purpose sweet sorghum varieties. Dual-purpose sweet sorghum varieties can produce grains for food, stalk sugary juice for bioconversion to ethanol and forage for animal feeds. Sorghum crop is regarded to have originated from Sub-Saharan Africa, largely because the region is home to maximum number of its species, particularly Ethiopia and Sudan areas [3,4,5]. Although several wild species of sorghum cultivars were collected from India, it has been argued such findings do not support the argument that cultivated sorghum has an independent origin in India; this is simply because all the collected Indian species are found in Africa as well [2-5]. Various literature has shown that sorghum originates from Africa, particularly from Sub-Saharan Africa [6,7,10]. Numerous research surveys have shown Sub-Saharan Africa contains the maximum diversity of both cultivated and wild species of sorghum [10,11]. The sorghum *genus* belongs to *andropogoneae* tribe of the family *Gramineae*; this includes both the “wild” and “domesticated” sorghum species respectively that are primarily cultivated for grains, silage or sugary juice production [10,11].

The Sweet sorghum *genus* has a haploid chromosome number that readily crosses with each other. Therefore, sweet sorghum along with other domesticated sorghum cultivars, are grouped under a single species called *Sorghum bicolor (L.) Moench* [2-3]. It has been suggested that sweet sorghum crop has been around in Ethiopia as early as 200AD, where local tribes cultivated it and chewed the stalk as a snack and for nutritional benefits while the grains were used in making of local beer [2-7]. It was during the Bantu tribe migration starting in 1000BC that the wide spread availability of traditional sorghum seeds became available in Western and Southern Savannah of Africa [3-5]. Furthermore, it has been reported that sorghum cultivars seed got to India also during the first millennium BC from the Eastern Africa and afterwards likely spread along the coast of South-east Asia and China province [4-5]. Sweet sorghum is also sometimes referred to as China cane or sorgos. It was around the end of last century that sorghum made its way to the Western region of the world widely, via Asia. Sweet sorghum got introduced in the Caribbean Islands and the Latin Americas via west Africa through slave trades route in the early 17th century as an alternative source for sugar production. In 1853, a New York nurseryman called William Prince introduced sweet sorghum in America (after receiving the seeds from France via China). He cultivated the crop in New York claiming that it was a potential new sugar crop and sold the seeds to farmers around Northern America for mass cultivation. In a similar effort, an American patent agent, J.D. Browne travelled to France and discovered French farmers efforts on sweet sorghum cultivation for sugar production from the sugary stalk juice. He observed that the crop is grown in places having similar climatic conditions favouring corn cultivation. Based on these observations, Browne collected sweet sorghum seeds from France and sent them back to the patent office with the advice that the crop could be considered as an alternative to sugarcane for sugar production. Browne further suggests the crop could be cultivated in America's corn-belt arears such as American North and the Midwest regions [5-6,10-12]. Sweet sorghum is also known as the "Chinese sugarcane" in America, presumably because it arrived America through France via China. Since the identification and proliferation of sweet sorghum seed availability around the world, several species have been domesticated and utilised for both domestic and industrial end-use applications. In addition, on-going researches worldwide is geared towards continued improvement of traditional seed varieties and development of new hybrids.

SWEET SORGHUM CULTIVATION

In spite of the agronomic similarities between sweet and grain sorghum varieties, standardized cultivation management procedures applicable to grain sorghum cultivation may not wholly be applicable to the sweet sorghum varieties. Sweet sorghum varieties tend to require more cultivation water relative to the grain sorghum varieties. Furthermore, sweet sorghum stems are more vulnerable to various insect attack (due to sugar accumulation) compared to the grain sorghums, hence, insecticides control requirement and management may vary [10,13]. Sorghum cultivation practice varies across the globe. While in some instances seed planting procedure is fully mechanised, in other instances it is conducted manually. Sweet sorghum cultivation management practice depends on individual farmer's capital investment, local cultural orientation, agronomic practice and government regulations. In Sub-Saharan Africa, for example Nigeria, sweet sorghum seeds are sown by bullock-drawn seed drills with either 2 or 3 coulters at 5-7cm depth into the soil. The seeds are sown in rows that are 45cm apart and the seeds are planted at about 15cm interval distance on each row and 10cm depth minimum. The seed rate is usually 8-10kg/ha, under rain-fed condition, the estimated plant population is about 54,000 crops/acre while with additional irrigated support facility the plant population ranged 60,000-72,000crops/acre [11,13-14]. Soil condition and type, seed variety, climatic conditions and local cultivation practice collectively influence the success rate for sorghum seed sowing. In addition, fertilizer composition and application rate, insecticides and pesticides management dictate successful cultivation management in sweet sorghum farming. Typical fertilizer input for sweet sorghum cultivation in Nigeria for example is 30-60kg/ha of P, 60-120kg/ha of K and 150kg/ha of N respectively [14].

Sorghum is generally a self-pollinating plant, however, under certain conditions, cross pollination occurs but this constitutes less than 10% of the total pollination activities. Sweet sorghum can be cultivated year-round, with an average of 4-5 months growing cycle and two crop cycles per annum is very feasible. But in Sub-Saharan Africa, due to limited availability of irrigated land and the need to maximise use of cultivable land for food production, sweet sorghum is usually grown under rain-fed conditions and only one-crop cycle annually is most commonly achievable. Over 53% of total land worldwide planted to sorghum is located in Sub-Saharan Africa i.e. of the estimated 44 million hectares of land worldwide dedicated to sorghum cultivation, about 27 million hectares is located in Africa, of which west Africa has about 13 million hectares. Nigeria in Sub-Saharan Africa has over 6 million hectares of land to which sorghum is cultivated. Therefore, Nigeria is rated the 3rd largest sorghum producer in the world. However, less than 10% of the total land dedicated to sorghum production is utilised for sweet sorghum plantation in Sub-Saharan Africa. In spite of Africa covering over half of total land area planted to sorghum worldwide, it contributes less than 35% of the estimated annual 60 million tons total sorghum grains production output worldwide. Its contribution to annual global sweet sorghum juice production is less than 15%.

Among the major challenges faced in sorghum cultivation and productivity in Sub-Saharan Africa is limited access to improved seeds or hybrids to local farmers for cultivation. The situation is exacerbated further by lack of access to modern mechanised agro-machineries by the local farmers and in addition to limited availability of investment funds for procurement of agro-chemicals that are needed in good agricultural practice. These challenges among others constrains favourable crop yields in Sub-Saharan African countries compared to countries like China, USA and India. For example, average grain yield for traditional sweet sorghum varieties (commonly grown in Africa) is 1-2 t/ha and the extractible stalk sugar is typically less than 1.5t/ha. However, in the USA and India for example, over 5t/ha of grain yield and 6-8t/ha of extractible stalk sugar is obtainable. This is largely attributable to the improved seed varieties planted in the USA and India while traditional seed varieties are most commonly planted in Africa. in Nigeria, which accounts for over two-third of total sorghum produced annually from West Africa, average sorghum productivity is around 3 – 4t/ha [11,13-15]. Majority of local farmers in Sub-Saharan Africa have strong preferences for cultivation of grain sorghum over the sweet sorghum variety. This is likely due to the economic and social benefits derivable from grain production over stalk juice production. In near absence of improved sweet sorghum seeds to local farmers coupled with lack of sufficient farm investment funds, the majority of farmers in Sub-Saharan Africa are constrained to prioritise growing of traditional local grain sorghum varieties and pay less attention to sweet sorghum cultivation. Sorghum grains have wide domestic uses, most importantly as a major source of food to the rural populace in Africa and for industrial utilisation (such as in brewing and malting). However, sweet sorghum stalk is mostly chewed as snack (like sugarcane) while the industrial capacity utilisation (such as in ethanol production) is at its infancy in Africa at the moment [8-10].

The potential of sweet sorghum as a promising feedstock for sustainable bioenergy production is related to its high biomass productivity, short cultivation duration with minimal agro-chemical input and tolerance to range of environmental stresses. For example, sweet sorghum yields around 20 – 50tons dry biomass per crop cycle within 120 – 150days. Sweet sorghum crop has impressive capacity to absorb about 45tons of CO_2 per hectare for each crop cycle, depending on local cultivation practice and crop variety. Consequently, sweet sorghum crop has been suggested to be carbon neutral in terms of carbon emissions i.e. absorption and repartition of CO_2 emissions across the entire crop cycle and utilisation is virtually neutral as shown in Table 1.

Table 1 CO_2 absorption and performance for sweet sorghum crop

CO_2 Absorption	CO_2 Emissions	
Cumulative CO_2 absorption per crop cycle 45.0t CO_2/ha	Growing cycle =	1.5t CO_2/ha
	Bioconversion process =	8.5t CO_2/ha
	Utilisation (combustion) =	35.0t CO_2/ha
	Total =	45.0t CO_2/ha

Source: Grassi (2011)

Growth stages

Sweet sorghum, like other sorghum cultivars (such as grain and forage) are usually planted either solely (as monocrop) or intercropped with maize in Sub-Saharan Africa. The crop growth stages start by seed germination and ends at grains physiological maturity on the panicle (Figure 1). Duration of the crop growth cycles vary with planting date, variety planted, climatic conditions, cultivation practices among other factors. Normally, sweet sorghum cultivation and growth cycle takes about 4 – 5 months to complete in Africa [15]. Though sweet sorghum can tolerate varied climate conditions and can withstand wide ranges of biotic & abiotic stresses, it is naturally a warm-weather plant that requires high temperature to favourably germinate and grow. Preferable temperature ranges are 32 – 36^{o}C and daylight length of 10 – 14 hours is required for optimum crop growth and yield [11,13]. The optimum rainfall regime for sweet sorghum plant growth ranged from 550 – 1000mm and relative humidity of 15 – 50% respectively [15]. Therefore, preferably, sorghum seeds are sowed after the soil is sufficiently moist and the soil temperature is up to 15^{o}C [14]. Effective disease and pest management practice is very important during crop cultivation [16]. An interesting plant characteristic of sorghum crop is its ability to go into dormancy during growth period, under adverse conditions (such as drought), the crop goes into dormancy and utilises its limited available water for survival rather than growth. However, when favourable conditions return, the crop resumes back to growth [15-16]. For example, early drought occurrence causes the crop to stop growth and remain in vegetative phase (especially if it occurs before panicle initiation), however, crop resumes leaf production and flowering when favourable conditions for growth return [16].

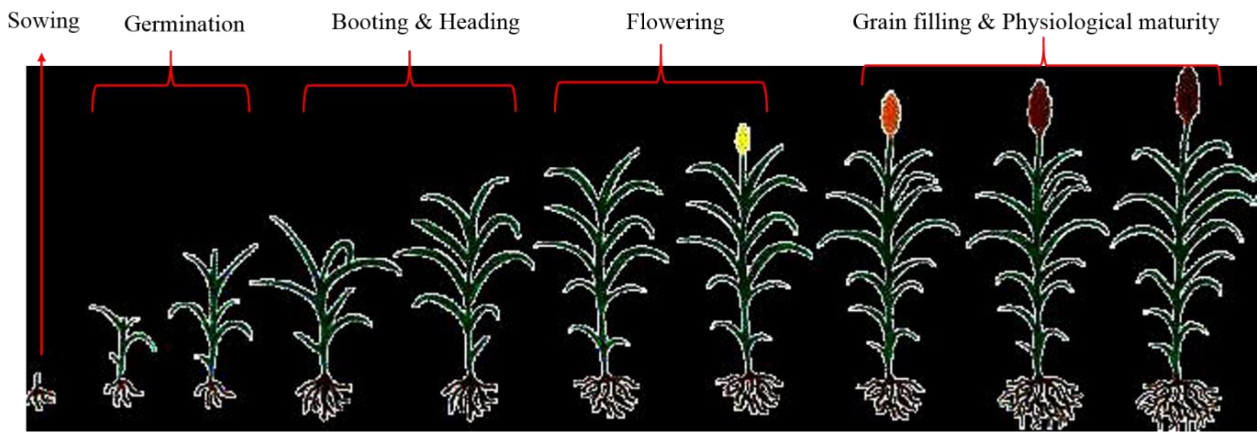

Fig.1 Sweet sorghum crop growth stages

Common diseases related to sorghum cultivation in Sub-Saharan Africa includes weed invasion, bacterial & fungal infections, insects, pests and quelea birds attack. The occurrence and severity of the disease infections varies seasonally, yearly, location and crop variety dependent, respectively. It may not be economically feasible to completely eradicate diseases in sorghums; hence, sorghum growers must be tasked to remain vigilance to avoid quelea birds and pest invasion on their sorghum farm through the adoption of an integrated pest management system. Furthermore, implementing other measures, such as; planting improved seed hybrids, good agronomic practice which included planting disease-free seed, proper seedbed preparation, accurate application of herbicides, insecticides as well as fungicides. These measures can help minimise losses from pests. Pests of sweet sorghum are similar to corn and sugarcane in Sub-Saharan Africa.

SWEET SORGHUM CROP MORPHOLOGY

Sweet sorghum simply refers to sorghum varieties containing high soluble sugars in their stalk. This distinguishes them from other sorghum varieties such as forage and grain sorghums that contain little or no soluble sugars in their stalks. Sweet sorghum is a C4 cereal crop with numerous cultivation advantages that includes efficient water use, fertilizer and radiation use efficiency, broad agro-ecological adaptation among others [5,7,8]. Sweet sorghum crop water requirement is about one-third that of sugarcane and about half that of maize. It has the capacity to absorb an estimated 45tCO_{2eq}/ha of carbon dioxide per crop cycle. It thrives well under cultivation conditions that are not tolerable to other cereal crops, it grows in semi-arid tropic areas, marginal lands, flooded lands etc [4,6]. Figure 2 shows morphology of sweet sorghum crop.

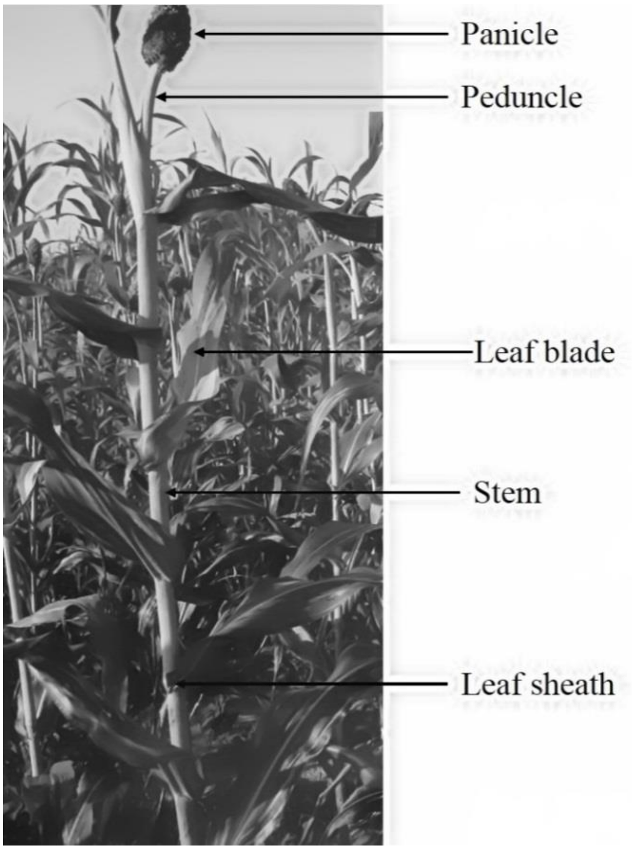

Fig. 2 Sweet sorghum morphology

Leaves and roots features

Sweet sorghum leaves are normally dark green and flat, similar to those of maize but less broad in shape. The total leave surface area of sweet sorghum plant is about half of that of maize. The leaves are composed of a long sheath that embraces the plant stalk at the nodes level and a matured blade which is about 100cm in length and 10-15cm width [5]. Mature sweet sorghum crop has 17 – 30 leaves depending on the sorghum variety and cultivation management, each leaf has stomata on both surfaces for efficient gasses exchange and transpiration [5-6]. An interesting characteristic of sorghum leaves is the presence of rows of motor cells along the midrib on the upper surface of each leaf. These cells can effectively roll up the plant leaves under moisture stress conditions. In addition to specialised leaves, the sorghum root system comprises 3 functional roots type i.e. primary, adventitious and brace roots respectively [5]. Normally, the primary roots develop from the radicle and die subsequently, thereafter, the adventitious roots develop from the underground nodes and may grow up to 2m in length. The adventitious roots essentially supply nutrients to the plant. However, the brace roots develop from the root primordia of the basal nodes above the ground level as shown in Figure 3. These are stunted, thick and normally appear above ground level. The brace roots primarily provide anchorage to the plant [4,5]. Generally, combined features of sorghum crop leaves surface area structure and its root system gives the plant its great tolerance for drought conditions.

Fig. 3 Sorghum crop root structure

Panicles

Sorghum grains are produced in clusters of flowers that are formed in relatively dense panicles (Figure 2). The emerging panicle is normally enclosed in a strong sheath until just the first flower opens. The panicle can produce up to 4000 kernels under favourable cultivation conditions. Sweet sorghum panicles vary in shape and size depending on cultivar type (Figure 4). The shape may be near oval, bearded or wiry and can be 70cm in length and 30cm in width. The sorghum panicle is regarded as a compound raceme in appearance i.e. a branched cluster of flowers wherein the branches forms the racemes. Each raceme strand further consists of one or multiple pairs of spikelets. These racemes vary in length depending on the number of nodes and the length of the internodes [4-5]. Panicle structure and shape is an important trait for sorghum cultivar identification and classification. Sweet sorghum panicles will usually fully emerge about 50 - 70 days after seed germination, depending on the sweet sorghum variety and cultivation climatic condition. With full emergence of the panicle, anthesis starts and typically reaches completion stage in about 6 days from the day the panicle emergence reach maturity. Flowering normally occurs 3 - 4 days after anthesis begins. Floral characters, such as anther colour, stigma colour, stigma length, length of pedicel, etc. are important traits for cultivar identification and classification [6].

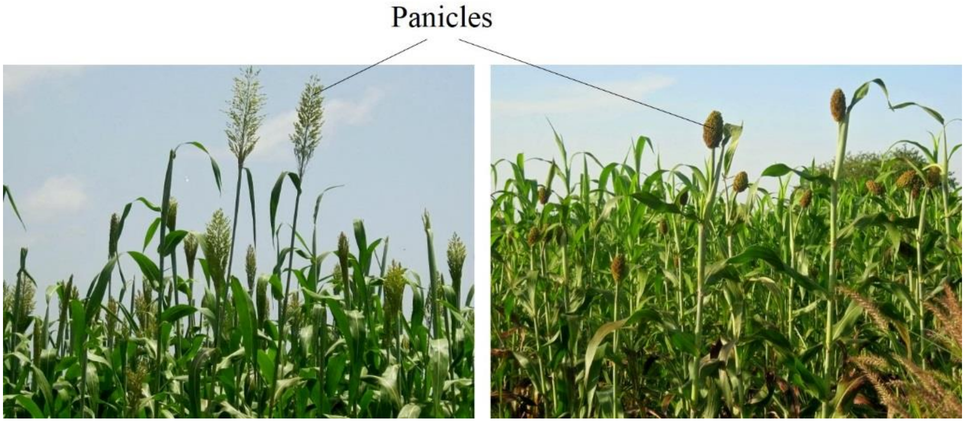

Fig. 4 Nigerian KSV8 and SSV2 sweet sorghum varieties panicles

SWEET SORGHUM GRAINS

Grains formation and maturation occurs on the plant panicles and follows certain sequential developmental stages i.e. milky, soft dough, hard dough before finally reaching physiological maturity. Depending on the sorghum variety, the grains developmental stages take about 30 - 45 days to completion i.e. for the grains to reach maximum dry weight of about 30% moisture content [13]. Sweet sorghum crop grains can be harvested at any chosen time when the grains appear to reach physiological maturity with 10-15% moisture content. However, for the traditional sweet sorghum varieties most commonly grown in Sub-Saharan Africa, the maximum accumulation of stalk sugars occurs before the grains reach the physiological maturity stage i.e. when the grains are at the soft dough development stage [13-14]. Therefore, sweet sorghum harvest by local farmers involves some kind of trade-off i.e. either allows grains to reach full maturity at the expense of decreasing stalk sugar accumulation or alternatively harvest the crop when stalk sugar is at its maximum accumulation stage but grains are yet to reach full maturity i.e. at soft-dough development stage. Therefore, it is imperative to intensify research efforts in Sub-Saharan Africa to develop improved sweet sorghum varieties that can yield both matured grains and stalk juice favourably i.e. without the need for grain-stalk juice trade-off at harvest time [14]. Depending on the variety, matured sweet sorghum grains weigh 20000 - 61000 kernels/kg on dry basis. The grains come in varied colours and shades; such as white, cream, brown, red, and black. and so on. In addition, the kernel hardness and chemical composition varies, depending on variety, cultivation condition, agronomic practice among other considerable factors [7-8]. Table 2 present some physico-chemical properties of sorghum grains.

Table 2 Typical chemical composition of sorghum grain (per 100 kernels).

S/no	Item	Amount
1	Energy	342Cal.
2	Water	12.0g
3	Protein	10.0g
4	Fat/Lipids	3.7g
5	Total carbohydrates	72.7g
6	Fibre	2.2g
7	Ash	1.5g
8	Calcium	22mg
9	Phosphates	242mg
10	Iron	3.8mg
11	Sodium	8.0mg
12	Potassium	44mg

Source: Ratnavathi and Patil (2013)

A cross sectional view of a sorghum kernel shows an outer seed cover (pericarp), the embryo (germ) and endosperm, respectively (Figure 5) [13]. The pericarp consists of several layers of tissues; the outer most layer called the epicarp is the kernel's surface cover and is made up of a waxy cuticle that may be pigmented from underneath the inner surface. Right beneath the pericarp layer is the testa tissue followed by the endosperm portion. Therefore, the testa is derived from the kernel's integument and is usually highly pigmented. The testa is source of the grain tannins, these are polyphenolic compounds that can impair nutritional value potential of the sorghum grains [14]. Usually, sorghum grains with pigmented testa and having visibly dark brownish or reddish coloured pericarp are regarded as likely containing condensed tannins. Condensed tannins usually combine with proteins to form complex molecules thereby significantly reducing the grains ease of digestibility. Studies have reported condensed tannins when ingested forms complex molecules with alimentary tract *proteases* resulting in slowed biodegradation of the complex molecules as well as carbohydrate polymers [15-17]. Nevertheless, in spite of negative nutritional effects attributed to condensed tannins containing grains, the crop varieties are continually grown in Sub-Saharan Africa, this is perhaps because of the crop's birds and insect invasion resistance [17]. In addition to the bird's invasion resistance potentials of the tannin containing grains, it is reportedly suitable for malting purpose applications [15-16]. Furthermore, certain polyphenolic compounds associated with condensed tannins present in some red sorghum grains give desired flavour and colour to certain traditional foods and beverages [18]. It is worth mentioning that polyphenols in sorghum grains can serve as source of natural antioxidants. Finally, the negative effects of tannins (phenolics) on nutritional value can be remedied by either removal of the grains testa layer via mechanical dehulling or by chemical charcoal treatment [12-14].

The endosperm is the starch storage tissue of the grain and constitutes over 75% of the total grain dry weight. The endosperm is normally segmented into an outer vitreous layer (horny) and an inner floury layer respectively. The endosperm is enclosed within a single-cell layer of aleurone tissue that is rich in oil and proteins [13]. Starch granules constitute up to 80% of the sorghum grain endosperm, with protein bodies embedded within. The protein bodies are more concentrated in cell layers nearer the aleurone tissues enclosing the endosperm. The embryo (germ) portion is embedded at bottom of the grain. The germ principally consists of 28% oil, 19% protein and 10% ash. In general, sorghum grains may come in different shapes and colours, but structurally, they are similar regardless of the sorghum crop variety [14]. Sorghum starch, like that of maize and wheat is an important source of carbohydrates [11]. Starch is essentially made up of amylose and amylopectin polysaccharides. Sorghum starch may be regarded as waxy or non-waxy in composition. Grains with near absence of amylose in their endosperm produce waxy starch i.e. the endosperm is virtually filled with amylopectin polysaccharides. Whereas endosperm containing 20 – 30% amylose produces non-waxy starch [15,17].

Amylopectin starch granules are crystalline in nature, therefore waxy starch requires relatively high gelatinization temperatures due to its crystalline structure. Starch functionality and application is directly related to its gelatinization energy value and pasting properties. Consequently, the swelling potentials of starch granules are strongly associated with the amylopectin content. However, amylose starch acts as a diluent and inhibitor of total starch swelling capacity. Compared to maize or wheat starches, sorghum starch has a higher amylopectin - amylose ratio. This results to the slow digestibility of sorghum starch compared to maize. For example, sorghum digestibility efficiency is 33% - 48% while that of maize is 53% - 58% [16,18].

Sweet sorghum grains have wide applications in domestic and industrial scale processes. Sorghum grains arguably account for over 50% sources of total calorific intake in Sub-Saharan Africa. The grains have multifarious applications that include production of malt, beer, malt extract?, sorghum meal, sorghum rice, livestock feed etc. Therefore, for a region like Sub-Saharan Africa that is faced with finding ways to address food security challenges, sorghum offers an attractive feasible opportunity. Despite the region having about 50% of the world's uncultivated land, it also has the lowest cereal self-sufficiency ratio compared to other regions of the world. With currently over 1 billion people residing in Sub-Saharan Africa, the present population is projected to increase about 2.5-fold by 2050. Cereal self-sufficiency ratio is a measure of total domestic cereal production divided by total cereal demand [18]. Consequently, Sub-Saharan Africa cannot afford growing sweet sorghum primarily for juice production (at the expense of high grain yield at harvest), this would further exacerbate the prevailing low cereal self-sufficiency ratio in the region. However, perhaps tannin containing sweet sorghum grain varieties may be grown and dedicated for stalk juice production rather than for grain harvests. In any case, the bitter grains could be use as adjunct in brewing and malting processes [17-19].

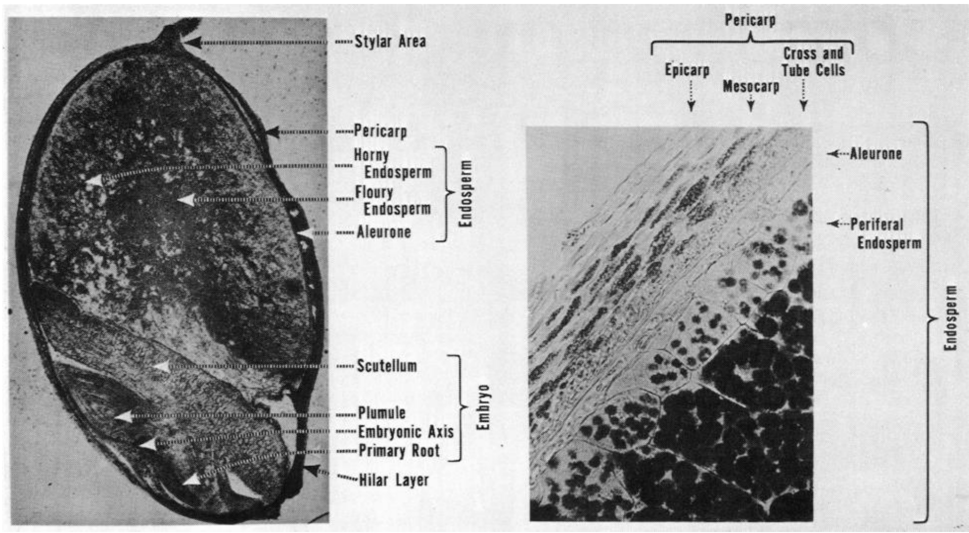

Fig. 5 Microscopic cross-sectional view of a sorghum grain.

Source: Wall and Blessin (1969).

Grain uses

Sweet sorghum varieties that retain up to 25% of their stalk sugars near the grain maturity stage are most preferable for cultivation. They serve as dual purpose crops which can produce both grains and stalk juice. Sorghum panicles can produce up to 4000 starch bearing grains. Over 80% of sorghum varieties cultivated in Sub-Saharan Africa are primarily grown for grain production, less than 15% are grown for livestock feed and juice production [19]. The grains have numerous uses and applications, they are widely consumed as staple food across

Sub-Saharan Africa for centuries. Sorghum grains have been valued as an important staple food in Sub-Saharan Africa for 3000 years [20]. Research advances in the past have mostly focused on development of sorghum hybrids that can produce improved grains only. However, with increasing interest on the use of bioethanol as alternative renewable energy source for road transport in Sub-Saharan Africa, research efforts are now geared development of sorghum hybrids with combine traits for improved grains and stalk juice yields simultaneously [20-22].

In terms of nutritional value, like grain sorghum varieties, sweet sorghum whole grain also has-many attractive features with nutritional benefits. The grains are rich in minerals, vitamins, phytoestrogens, and antioxidants that may protect against non-communicable disease [23]. These micro nutrients can help reduce stunted growth in children among other health benefits in adults. In terms of anti-nutritional content, sweet sorghum grains contain polyphenols and phytic acid. Polyphenols are secondary metabolites that inhibits digestibility of proteins; they bind protein molecules thereby rendering them unavailable for intestinal absorption [24]. In addition to protein binding, polyphenolic compounds also interact with carbohydrate polysaccharides to form insoluble compounds that are resistant to digestive enzymes activities [23-24]. Consequently, sorghum starch digests slowly compared to other cereals starches like maize and wheat. The slow digestion process of sorghum starch leads to reduced calories build-up and resultant energy supply over extended periods, this may help reduce obesity tendencies. In general, polyphenolic compounds in sorghum grains are classified as phenolic acids, flavonoids and condensed tannins respectively. The concentrations and composition of these phenolic compounds in sorghum grain depends on the crop variety and agronomic practice employed in sorghum cultivation [5,7]. Condensed tannins containing sorghum grains may not be directly palatable due to their bitter taste, however, they are suitable in beer brewing and other industrial applications [22]. Phenolic compounds are also sources of high level antioxidants and dietary fibres [21]. Subsequently, consumption of sorghum starch may be beneficial to diabetic patients and people at risks of some extravascular diseases.

Regarding the phytic acids in sorghum grain, like polyphenols, phytic acid also forms insoluble compounds with minerals such as calcium, magnesium, zinc, iron, sodium among others to decrease their bioavailability for metabolic activities [23-24]. Phytic acid concentration in sorghum grains flour ranges from 875 – 2212g/100g. This acid normally occurs in the bran and germ region of the whole grain. Further health benefits of sorghum starch are related to its being a naturally occurring gluten-free meal source. It is an attractive alternative ingredient source in diets preparation that traditionally contain gluten [25]. In the recent decades, there has been an increasing interest to utilise sorghum grains in the development of food products that would be suitable and safe for people suffering from celiac disease or wheat allergies [25-26]. In Sub-Saharan Africa where barley is rarely grown and wheat is occasionally in limited supply, sorghum grains are a promising substitute for barley and wheat in beer brewing and in a variety of gluten-free beverages and baked foods, respectively. It is expedient to mention though for decades sorghum grains were widely thought to be gluten-free, it was in 2007 that clinical tests were conducted and the claims substantiated [26]. Consequently, sorghum starch if appropriately processed holds huge potential to be a healthy and sustainable source of qualitative diet ingredients that may be added into numerous products to replace the bleached and refined flour meals majorly used in Sub-Saharan Africa as food ingredients [26-27]. In addition, food ingredients high in phenolic-rich sorghum bran could potentially improve the nutritional benefits of certain processed foods and the overall diets. In summary, sweet sorghum grains exhibit varied grain composition, colour and size depending on crop variety [5,7]. Sorghum starch offers numerous potential health benefits, it lingers in the digestive tract longer than starches from other cereals thereby generating extended energy while restricting calorie intake. The starch is virtually gluten free and an inexpensive source of phenolics as well as dietary fibre [24-26]. In Sub-Saharan Africa where population is rapidly growing, sorghum can be considered a potential food source to combat extreme hunger and acute malnutrition in children.

Sorghum grains are processed into variety of diets in different parts of Africa. Common delicacies prepared from sorghum grains include [25-27]:

1- *Tuwo*; a kind of pudding prepared from floured decorticated sorghum grains, the flour is cooked with water under constant stirring. The cooked mixture forms thick paste that after cooling to room temperature becomes solid. The solid *tuwo* is eaten with variety of local soups, e.g. vegetable soup.
2- *Bogobe:* This is a porridge sorghum grain meal normally eaten with vegetables. It can either be prepared from fermented sorghum grain (usually 24hrs fermentation) or unfermented. The fermented meal is commonly known as *ting* while the unfermented meal is called *mosokwane*.

3- *Ogi & Ugali:* These are forms of local pap prepared from water-soaked sorghum grains. The soaked grains are milled with water addition, the mixture is allowed to settle. The thick bottom slurry is used to prepare local *ogi* or *ugali*.

4- Varieties of many bakery related products such as *injera*, *kisra*, *ajin* among others are prepared from processed sorghum grains. These serves as important staple source for significant local population of Sub-Saharan Africa.

Gluten-free sorghum grain brewing

Gluten is a storage protein found in wheat, barley, rye, triticale and possibly oat, and it is the main structure-forming protein in flour. Gluten is a harmful substance for individuals suffering from celiac disease (CD). CD is the result of interaction between genetic and environmental factors and the only medical treatment is a gluten-free diet at present. The notice of gluten-free foods and beverages is increasing as diagnosis of CD increases. CD is a genetic immune media enteropathy which is triggered by the ingestion of gluten[28]. Screening tests showed that there is a high prevalence of CD among both healthy children and adults. The screening tests show that CD is one of the most frequent diseases, as a genetic based disease, and occurs in a ratio of one person to 130 – 300 persons in the European population[28].

There is no international agreement over the term "Gluten-free" or universal symbol that makes gluten-free products distinguishable. However, gluten-free products are defined as food[28]:

a) "Consisting of or made only from ingredients which do not contain any prolamins from wheat, durum wheat, rye, barley, oats, or any Triticum species such as spelt (*Triticum spelta L.*) kamut (*Triticum polonicum L.*) or their crossbred varieties with a gluten level not exceeding [20 mg/kg] in total based on the food ready for consumption;

b) Consisting of ingredients made from wheat, rye, barley, oats, or any Triticum species such as spelt (*Triticum spelta L.*) kamut (*Triticum polonicum L.*) or their crossbred varieties, which have been rendered 'gluten-free'; with a gluten level not exceeding [100 mg/kg] in total based on the food ready for consumption;

c) Any mixture of the two ingredients as in (a) and (b) with a gluten level not exceeding [100 mg/kg] in total based on the food ready for consumption."

African traditional sorghum beer brewing

The art of brewing with cereals such as sorghum, millet and maize to produce intoxicating (alcoholic) liquors has a long tradition. In brief, the following processes are involved in the production of opaque sorghum beers in Nigeria.

Steeping and germination

Sorghum grains are soaked in water for approximately 2 to 3 days. In modern technology, this is the steeping process. After soaking in water (steeping), grains are spread in heaps (4 to 7cm thick) on jute bags and allowed to germinate. This is the malting process. The jute bag acts to retain moisture, which in turn reduces the incidence of sprinkling with water. This of course, will enhance microbial infection, especially if rapid germination of grains is not achieved at the start of germination. Germination lasts for 3 to 4 days. After germination grains are thinly spread out on concrete floor in the sun to dry to arrest germination. This is the kilning process. A temperature range of 40 to 50^{o}C can be achieved depending on the season of the year. This temperature is enough to arrest germination but is not sufficient to impart to the malt the desired flavour as well as colour as is the case with kilned barley malt. This is probably why a creamy colour is obtained from opaque beers.

Mashing and fermentation

To brew, the sun-dried sorghum or millet malt is milled and mashed. During the mashing process, milled malt is mixed with water at a suitable grist/liquor ratio. Different ratios may be used to produce different kinds of products. After mashing, the mash is filtered through special types of cloth just fine enough to trap only coarsely milled particles. The filtrate is then transferred to a collecting vessel used in a previous brew. This previously used fermenting vessel is the major source of fermenting micro-organisms. Fermentation lasts for 2 to 3 days, after which the opaque beer is boiled and then, matured for about 2 days. After pasteurization at 60-65^{o}C for 30 minutes the beer is ready for consumption. Such beers may have a short shelf life of 1-8 days. Short shelf life may be due to very low lactic acid content (0.3-0.6%), low titratable acidity (0.4-0.6%, as acetic acid), low alcohol content (2-4% v/v), and/or high concentrations of vitamins and fermentable sugars[29-30].

Some points to note:

- The processes involved in the production of traditional opaque sorghum beers (steeping, germination, kilning, mashing and fermentation) are comparable to those followed in the production of conventional clear European beers, except that the science of production was not well understood.

- The use of previous collecting vessel as a source of fermenting micro-organisms implies lack of control on the mixed micro-flora of the fermenting vessel.

Nutritive value of opaque beers

Opaque beers have a high nutritive value because of its particulate composition[31-33]. These particles contain starch, proteins and vitamin B[34]. Since de-rooting is not carried out after germination and kilning, significant quantities of amino acids and peptides of the roots and shoots are carried over into the beer[35-36].

Popular Locally Brewed Alcoholic Beverages in Nigeria from sorghum and millet

Production of local alcoholic beverages in Nigeria from cereals is very popular. The major raw materials used are sorghum, millet and rice. Interestingly, these cereals fall into the category of gluten-free cereals as such suitable for celiac sufferers. These locally brewed alcoholic beverages satisfy both the cultural and social aspects for the large population in Nigeria. Some of the popular locally brewed alcoholic beverages include *Burukutu* (BKT), *Pito* and *Kunnu*. Production of alcoholic beverages also undergo similar processes as applied in the modern brewing industries such as malting, mashing and fermentation. The major difference is lack of understanding the science involved in these processes.

Burukutu

In Nigeria, a popular local alcoholic drink, *Burukutu* popularly known as "BKT" if brewed from fermented sorghum and other protein enriched grains. It is produced traditionally through a method that involves malting, mashing, addition of an adjunct, fermentation of sorghum using an old brew as a starter culture for 48h pasteurization by boiling and maturation. It serves as a source of alcohol for the old and young, male and female, educated and uneducated.

Pito

Pito, another popular fermented alcoholic drink in Nigeria is closely related to *Bururkutu* as both alcoholic drinks are produced mainly from the grains of guinea corn (Sorghum vulgare and Sorghum bicolor). Pito is however, a sweetened variant and bye-product of *Burukutu* as it is usually filtered off from the top, and *Burukutu* is the sediment that settles at the bottom of the brew mix and is usually heavier in concentration. Therefore, *Pito* is lighter and more like the refined part of the brew. It is highly intoxicating, but relatively cheap and can be consumed anytime of the day-morning, afternoon and night.

Kunu

Kunu is another traditional non-alcoholic fermented beverage popular in different parts of Nigeria. The beverage which is millet-based is milky cream in appearance and it is consumed within few hours of its production by people within the low to middle income bracket who usually cannot afford industrially produced beverages. The drink has two versions*: Kunun Zaki* , where the main ingredient is millet and *Kunun Gyada*, where the main ingredient is groundnut, sometimes can be sprinkled with rice. Rich in protein and high in fiber and nourishing vitamins and minerals.

Gluten-free products and beer from sorghum and related cereals

Sorghum, a sustainable ancient grain that originated in Africa, is now grown in many countries around the world including the United States. Sorghum, often referred to as "the camel of crops", grows using less water and other natural resources. Naturally gluten and GMO free, sorghum is ideal for individuals with celiac disease, gluten intolerance, or gluten sensitivity. Nu Life Market is one of the largest gluten free flour mills in the United States that control all aspects of milling to produce a custom particle size, from whole grain to fine bakery flour. Nu Life has produced products from different sorghum varieties which include: white sorghum, waxy white sorghum, black sorghum, burgundy sorghum, waxy burgundy sorghum and sumac sorghum[28].

The development of gluten-free products is increasing in many countries. In the brewing industries, a lot of 'gluten-free beer' is available in the market, and this type of beer broadens the range of beverages which is consumable for a patient who suffers from CD. Due to their chemical composition, maize, rice, sorghum, the pseudo-cereals (amaranth, buckwheat and quinoa) are suitable raw materials for brewing gluten-free beers. Currently, a lot of gluten-free beer is produced from these raw materials. Table 3 shows some examples of gluten-free beer that are produced at present. Also, many technologies for brewing gluten-free beers are available, and many patents have been approved and being applied.

Table 3. Gluten-free beers that are produced at present.

Gluten-free beer	Producer	(ABV) %	Comments
Redbridge	Anheurser-Busch	4.8	Made with sorghum, remains the most visible gluten-free beer on the US market
Bard's Tale	Bard's Tale Beer Company	4.6	The only beer brewed using 100% sorghum
New Grist	New Grist, Lakefront Brewery	5.7	A Pale beer made from sorghum and rice

Green's	Green's Gluten-free Beers	6-8.5	Four types of beer made with millet, sorghum, rice and buckwheat
St Peter's	St Peter's Brewery	4.2	Made from sorghum, a clean, crisp gluten-free ale with a pilsner-style lager

Source: Cureton and Fasano (2009).

Modern brewing with sorghum as raw material

When brewing with local raw materials (mainly sorghum) was introduced in Nigeria in 1988, major breweries were confronted with big challenges due to lack of adequate preparations to switch from barley malt to sorghum grains. The consideration on the use of local cereals for brewing lager beer did not take cognizance of the fact that breweries, like other food industries, are conservative and will strongly resist change. Since the ban on the use of imported malted barley became effective in Nigeria, large volumes of Continental-type lager beers and ales have been brewed in Nigeria with huge success[37]. Indeed, one of the key players in brewing in Nigeria has built a huge sorghum malting plant[38] (Figure 6).

Fig. 6 A $250 million brewery with an annual 30,000 tons sorghum grains malting capacity (Ogun, Nigeria).
Source: Afolabi (2018).

Table 4 shows the typical range of values usually obtained from the worts of sorghum when sorghum is malted at a temperature range of 20^{o}C and 30^{o}C and mashed at their optimal mashing temperatures. The results in Table 4 show the typical range of values (amino acids) usually obtained from the worts of sorghum when sorghum is malted at a temperature range of 20^{o}C and 30^{o}C and mashed at their optimal mashing temperatures[39-40].

Table 4 Properties of Wort of Sorghum Germinated at Different Conditions**

Parameter	Analyses range of values
Total soluble nitrogen (%)	0.52-0.74
Free amino nitrogen (mg/L)	133-205
Glucose (g/L)	14.5-15.3
Fructose (g/L)	2.0-3.2
Sucrose (g/L)	0.2-0.3
Maltose (g/L)	20.3-21.0
Maltotriose (g/L)	8.0-9.1

** Values will also depend on the sorghum variety.
Source: Ugboaja, Bednarski and babuchowski (1991); Van Heerden (1989).

The close range of values in Tables 4 and 5 are noteworthy as they show that malting temperature will not have an adverse effect in producing malt of consistent quality when sorghum is malted. This is important in a world where not only the growing environment for cereals are changing, but also the processing environment as malting temperature is difficult to control.

Table 5 Properties of Wort of Sorghum Germinated at Different Conditions

Amino acid profile (µMole/L)	Analyses range of values
Aspartic	0.360-0.386
Glutamic	0.401-0.421
Asparagine	1.290-1.306
Glutamine	2.502-2.662
Serine	0.366-0.372
Arginine	0.348-0.372
Threonine	0.223-0.225
Glycine	0.503-0.510
Alanine	1.110-1.318
Proline	2.186-2.440
Valine	0.612-0.650
Methionine	0.192-0.196
Isoleucine	0.428-0.459
Leucine	0.982-1.090
Trytophan	0.171-0.193
Phenylalanine	0.669-0.716
Lysine	0.478-0.480
Histidine	0.295-0.317
Tyrosine	0.992-1.136

Source: Ugboaja, Bednarski and babuchowski (1991); Van Heerden (1989).

Generally, sorghum, an ancient grain with its origin from Africa is a promising cereal that will help provide food security in a world that is getting warmer. Aside from sorghum producing crop under harsh growing environment for cereals, sorghum is a good source of raw material for producing gluten-free diets and alcoholic beverages. It is a cereal of great importance to be used in providing food and beverages for celiac suffers. The use of sorghum to brew alcoholic beverages will benefit low income people in different parts of the world as well as brewing the Continental-type beers and ales.

SWEET SORGHUM STALK JUICE CHARACTERISTICS AND USES

There are varieties of sorghum that produce sugary stalk juice. Sweet sorghum crop varieties efficiently convert free atmospheric carbon dioxide to sugars that accumulates in the stems. The stalk juice contains variable amounts of fermentable sugars, proteins and starch. Less than 2% of these sugars accumulates in the crop panicle and leaves [27]. Fermentable sugars formed in the sorghum stalks are predominantly, glucose, fructose and sucrose. Additionally, other sugars such as xylose, arabinose, galactose and maltose are also formed but in low concentrations [26-27,41]. The composition of sweet sorghum stalk juice varies, the constituent concentrations level largely depends on many factors among which are crop variety, crop development stage at harvest, agronomic practice and climatic conditions [41]. During sorghum crop growth, fructose tends to be the sugar in higher concentration at crop's early growth stage, however, sucrose is most likely the predominant sugar after the crop heading [27]. Sucrose accumulation in sorghum stalk normally starts after crop heading and attains maximum concentration when the grains subsequently reach soft-dough growth stage [41]. However, for the improved crop varieties and hybrids, stalk sugar accumulation increases after the plant reaches its flowering stage and continues to its maximum accumulation until grains reaches physiological maturity [25-26, 41]. Therefore, the most favourable harvesting time for sweet sorghum crop should be determined by direct measured values of the total sugar concentrations and grains degree of physiological maturity. It is pertinent to mention some literatures broadly classify sweet sorghum varieties into saccharin-types and syrup-types [41-42]. The saccharin-type sorghum juice contains sucrose as its predominant sugar while fructose sugar is present in low concentration. Sucrose sugar easily crystallizes during heating, this makes it suitable for refine sugar production. However, the syrup-type sorghum juice contains sufficient fructose sugars that is enough to inhibit sugar crystallization, thus, the syrup-type sorghum juice is not suitable for refine sugar production but suited for syrup production. In addition to sugars, sorghum juice also contains essential amino acids, crude proteins and minerals needed to maintain normal vital functions in humans [41-42]. Maintaining such vital functions in adults requires daily intake of 100-400mg of calcium, 200-300mg of magnesium, 0.9mg of iron etc. While occasionally this requirement may be met via normal food consumption, normal food may not sufficiently provide these minerals and their inadequacy in the body causes some kinds of illness. For this reason, some fortified drinks with calcium and zinc may be taken as supplement source, however, sorghum juice naturally rich in these minerals may be considered an alternative source to fortified drinks [43].

Furthermore, proteins and amino acids function as an organic buffering system that maintains pH value stable in humans. Balanced diet is majorly the source of essential amino acids to the body. It is therefore worth noting that the nutritional value of a drink depends not only on the amount of nutrients, but more importantly on the nutrients composition [41-42]. Sorghum juice contains numerous kinds of nutrients with relatively stable proportion and amount as shown in Table 6. It is pertinent to mention of the human essential amino acids, lysine, phenylalanine, valine, methionine, leucine, isoleucine and threonine are found in the juice, histidine essential to babies is also found, all these constitutes free amino acids as represented in Table 6.

Table 6 Typical sweet sorghum juice chemical composition

s/no	Constituent	Concentration
1	Juice yield	23 – 45m^3/ha
2	Starch	0.31 – 1.2g/l
3	Crude proteins	1.1 – 1.9g/l
4	Free amino acids	115 – 340mg/l
5	Sucrose	36 – 117g/l
6	Glucose	20 – 35g/l
7	Fructose	10 – 15g/l

Source: Roland, Holou and Stevens (2012).

Generally, sorghum juice is considered suitable for consumption and can serve as an alternative to refined cane sugar consumption. In some Sub-Saharan African villages, refined cane sugar supply is limited and sometimes the price not affordable to the locals, sorghum juice syrup serves as a suitable alternative sweetener. Additionally, some locals hold strong opinions that sorghum juice syrup is healthier to consume than refined cane sugar (though no medical science has yet substantiated such believe). To produce sorghum juice syrup, freshly extracted sorghum juice must be strained through fine mesh screen and afterwards allowed to settle undisturbed in settling tank under ambient condition for about 2-3 hours. The supernatant fraction is decanted into an evaporation pan and gradually heated to about 105°C until the sugar brix reaches 74 – 76%. While evaporation heating is in progress, it is important to continuously stir for efficient skimming of coagulating materials that have risen to the syrup surface be efficiently removed. Furthermore, to prevent the syrup from getting burnt or the colour becoming dark brown after heating to 105°C, the syrup must be rapidly cooled to 80°C in less than 15min and thereafter transferred into sterilised bottles for shelf keeping [41-43]. The foam and froth produced during syrup heating and the residual solutes at the settling tank bottom can be processed to livestock feed or organic fertilizer. The syrup is usually consumed as an alternative to either cane refine sugar or honey in beverage preparations. Appropriately prepared sorghum syrup is rich in minerals and calories similar to natural honey as shown in Table 7. The equipment type and production processes employed for syrup production dictates the process efficiency in terms of syrup yield and quality [42].

Table 7 Chemical composition of sorghum syrup compared to honey

Constituents	**Sorghum syrup**	**Honey**
Calorific value (cal./g)	2.60	3.26
Total soluble solids (% wt.)	77.00	81.00
Proteins (N × 6.25) (% wt.)	1.65	--
Ash (% wt.)	3.69	0.59
	mg/100g	
Calcium	160.00	5.00
Phosphorous	11.00	4.10
Riboflavin (Vitamin B2)	10.00	0.06
Vitamin C	11.50	5.00
Nicotinic acid	153.00	32.00
Iron	0.86	0.59
Sodium	86.00	4.70
Potassium	1810.00	90.00
Sulphur	Not detected	8.00

Source: (Roland, Holou, and Stevens (2012); Mukabane, Bonface, Thiongo, Gathitu, Murage, Ojijo, and Willis (2014).

Factors that may lead to poor quality syrup production from sorghum juice include; inefficient removal of scum that may result to presence of floating mass causing cloudy appearance to syrup, juice with high starch content may form gels in syrup during cooking, juice with high sucrose content may also partially crystallizes during cooking etc. Further sorghum juice use is in sugar-cake production. Freshly extracted sorghum juice can be blended with cane juice and boiled until thick paste is formed, the paste is allowed to cool to room temperature and solidifies. The cooled sugar cake is locally known as “mazarkwaila” in Nigeria and use as a sweetener.

Recently, the fermentable sugars component of sweet sorghum has been attracting attention as a potential sustainable feedstock source for bioenergy production in Sub-Saharan Africa [23,25]. The U.S. department of agriculture suggests that the ratio of total energy invested to grow and process sweet sorghum to deliverable energy to the full utilisation is estimated at 1:8 [24]. This ratio may further be improved when efficient production engineering and plant molecular breeding technologies were employed in the processes. It is established that gradual substitution of petroleum with bioethanol as transport fuel would greatly reduce annual GHG emissions in Africa [5-9]. For example, it is projected that cultivation of improved sweet sorghum crop with at least $35m^3$/ha juice yield and 21% sugar brix could support production of 61 billion litres of bioethanol annually in Sub-Saharan Africa [9]. The projected investment cost to achieve this feat is an estimated 28 billion USD on the industrial sector and 47 billion USD on the agricultural sector respectively. This investment may generate over 10 million direct and indirect jobs, lead to displacement of over 25% of petroleum consumption in the transport sector and replacement of 100% of kerosene consumed as cooking fuel. Consequently, over 300 million tons of CO_2 emissions would be reduced annually, particularly when the crop’s lignocellulosic biomass residue is utilised in power generation [5,9,11,16,21]. In general, thermochemical processes such as combustion, pyrolysis and gasification can be employed to convert the lignocellulosic residue of sweet sorghum harvest to heat and electricity. Perhaps another interesting use of sorghum juice as potential feedstock is in production of lysine. Research has shown yeast extract and peptone supplemented sorghum juice can be a substrate that supports growth of auxotrophic mutant *Corynebacterium glutamicum* thereby producing lysine up to 28.8g/l concentration at a sugar conversion efficiency of 0.23g/g [7-9]. Further utilization of sweet sorghum juice as feedstock for lysine production by fermentation could potentially be used to upgrade livestock feeds low in lysine contents. Blending lysine containing fermentation broth with a relatively dry substrates like maize or sorghum distillers’ dry grains with solubles (DDGS) from ethanol production could result to upgrading the DDGS product to a substantially higher value as livestock feed.

Crop harvest

Studies have shown sweet sorghum crops harvested during rainy seasons yield higher juice sugar and slightly lower grains compared to post-rainy seasons harvest; as much as 54% more juice sugars and 9% less grains may be obtainable [43]. Therefore, there is relatively less trade-off concern between stalk juice and grain yields when sweet sorghum varieties are to be harvested for stalk juice production during rainy season. Further ongoing research is focused on improving the sugary stalk juice and grain traits simultaneously for improved harvest during all seasons [41-43]. In Sub-Saharan Africa, sweet sorghum is usually harvested manually. The crop is harvested when grains reach physiological maturity i.e. at about 10 – 15% moisture content dryness (depending on variety). Late harvesting (i.e. allowing grains to reach full dryness) can result to spontaneous shedding of the grains from the panicle and the stalk juice will significantly reduce in quantity and quality. Grains with up to 25% moisture content can be harvested but would require subsequent sun drying before storage. The grains may be stored as unthreshed or threshed produce before storage [9,11,13]. Traditionally, grain threshing in Africa involves arranging the sun-dried sorghum panicles on the ground and beating them with sticks or alternatively crushing the panicles in a mortar and pestle. The amount of time required for threshing largely depends on sorghum variety and level of grain dryness. After threshing, the grains are separated from the chaff by wind winnowing. The winnowed grains are dehulled by hand-pounding in mortar and pestle, this traditional method is time consuming and arduous. However, there are modern machineries which employs mechanical processes that efficiently run the threshing and dehulling processes effectively. Grain yields of 0.5 – 4.0t/ha is usually expected from local sweet sorghum varieties grown in Sub-Saharan Africa, depending on variety and cultivation practice [5-6].

For juice extraction, the stalks are usually roller milled. To further improve on sugar recovery, the stalks may be shredded or peeled-off before milling. Depending on crop variety and growth stage at harvest, sweet sorghums grown in Sub-Saharan Africa typically shows total juice sugars in terms of degree ^{o}Brix ranging from 14- 25% while the sugars concentration varied from 55-180g/l and juice yield of 15-26m^3/ha [9,11]. The extracted raw juice needs further clarification and purification before usage or storage. Appropriate liming of the raw juice followed by saturation with carbon dioxide will result to precipitation of the unwanted solutes in juice, further filtration will enhance the juice purity. The “lean” juice obtained (after precipitation) may be thickened by evaporation to improve the sugar concentration i.e. from 15% to 70% sugar content. It is worth noting that sorghum stalk juice should be expeditiously extracted immediately after crop harvest, preferably not more than 24 hours after harvest. This is to minimise sugar loss due to evaporation and microbial activity in the course of storage of the harvested stalks. After juice extraction from the stalks, the residual crushed stalks along with the threshed panicles and leaves are collectively regarded as bagasse i.e. green wastes. Therefore, bagasse is a fibrous material consisting of lignin, cellulose and hemicellulose polymers. In addition to containing some residual sugars (from crushed stalks). Sweet sorghum bagasse is also rich in nitrogenous compounds, making it attractive as livestock feed. Sweet sorghum crop yields 10-55t/ha fresh bagasse while the dried bagasse can weigh about 7-40t/ha. Soil condition, agronomic practice, climatic conditions and crop variety influence bagasse yield [5,7,13].

Juice extraction and processing

In practical terms, the sugary juice from sweet sorghum stalks is predominantly composed of sucrose, glucose and fructose. The juice is usually extracted by crushing or shredding of the prepared stalks using a set of traditional roller mills or a modern one pass tandem mill. If the time lag from stalk harvest to milling is longer than 2 days, this may result to huge loss of potential recoverable sugars due to microbial activities [41-42]. Studies have shown invertase enzymes hydrolyse sucrose to its respective reducing sugars namely fructose and glucose (i.e. enzymatic inversion of sucrose sugar). With increasing delay before stalks are milled, there will be increasing microbial activities which would hasten deterioration of the juice content in the stalk; production of invert sugars, polysaccharides (such as dextran and levan) along with other microbial contaminants (such as ethanol and lactic acid formation) will have negative effect on subsequent juice processing [42]. Therefore, freshly extracted juice needs to be further heat treated at about 65^{o}C to terminate or limit microbial activities that may result to impairment or contamination of the juice quality, particularly if extended storage of the juice is required [41]. The major concern regarding handling of sweet sorghum juice is the short shelf life of the juice largely due to its high sugars and relevant amino acids contents that favours contamination by the spoilage microbes. Consequently, appropriate preservation and proper storage of sweet sorghum juice is necessary for its further utilization, especially in syrup or ethanol production. Normally, the juice is sterilized, clarified and concentrated to desirable level considered suitable for subsequent applications. The concentrated fresh juice can be stored at temperature range of 15-18^{o}C for up to 24 hours on shelfs. If the shelf life preservation is required for up to 3 days, the juice may be spiked with chemicals such as citric acid, sorbic acid, sodium benzoate and so on. Spiking juice with appropriate chemicals helps minimise the deterioration rate and losses, otherwise, up to 16% of the sugars may be lost to microbial activities and making it slightly sour to taste. However, for extended shelf life of up to 10 days, the juice can be pasteurized at a temperature of 85^{o}C for 10min followed by filtration, afterwards, the treated juice can be stored at up to 35^{o}C ambient temperature for 10 days without significant juice deterioration[21,23,41].

Bagasse

Bagasse is a fibrous material generated after crop harvest and stalk juice extraction. The quantity and quality of sweet sorghum bagasse largely depends on the plant variety, agronomic practice, climatic environment among other factors. Principally, sorghum bagasse composed of lignin, cellulosic and hemicellulosic biomass [23-25]. The cellulose and hemicellulose are polysaccharide polymers that are intertwined by tough lignin fibre. The lignin material acts as a barrier to efficient enzymatic hydrolysis of the cellulose and hemicellulose polysaccharides. Therefore, the amount of lignin fraction contained in the lignocellulose biomass determines its digestibility efficiency [7-11]. Consequently, to effectively utilise lignocellulosic materials as feedstock source for say bioethanol and other chemicals production, it is imperative to reduce the fibrous complex material into its separate basic components i.e. lignin, hemicellulose and cellulose respectively. To achieve effective separation, a pre-treatment process is essential to breakdown the lignocellulosic matrix. The pre-treatment process can be via physical, chemical or biological platform. The pre-treatment process is followed by hydrolysis procedure of the polysaccharides (i.e. cellulose and hemicellulose) to break them further down into their respective monomeric units i.e. glucose, pentoses and hexoses etc. Table 8 shows typical phytochemical composition of sweet sorghum bagasse.

Table 8 Proximate analysis of sweet sorghum bagasse (dry weight)

s/no.	Constituent	Composition
1	Hemicellulose	35 – 50%
2	Cellulose	15 – 25%
3	Lignin	20 – 30%
4	Total starch	5 – 12%
5	Total protein	3 – 10%
6	Net calorific value	4125Kcal/kg.
7	Bulk vol. @20% humidity	150kg/m^3

Source: Nasidi, Agu, Deeni and Walker (2013).

The efficient degradation of complex lignocellulosic biomass to yield individual fractions of cellulose and hemicellulose polysaccharides is necessary to optimally derive sugars that can be utilised in numerous applications [27]. The intertwined lignin, cellulose and hemicellulose matrix forms a physical barrier that grossly limits biodegradation enzyme access to polysaccharides and protein substrates for efficient degradation [13]. However, depending on lignocellulosic degradation process chosen, toxic compounds that hinders biodegradation processes are generated at various treatment levels. For example, the range of lignocellulose degradation by-products likely to be generated included phenolic compounds from lignin and acetic acid that is derived from deacetylation of hemicellulose xylose side chains. Additionally, formic acid is generated from degradation of furfural or 5-hydroxymethyl furfural [5,11,15,23]. Nevertheless, sweet sorghum bagasse is a promising feedstock source for numerous industrial applications. For example, cellulose derived from bagasse can be utilised as important raw material source for the pulp and paper industry. With recent technological advances in the development of second generation bioethanol (lignocellulosic derive ethanol), sweet sorghum bagasse is fast attracting attention as potential feedstock source for sustainable ethanol production, especially in Africa where corn, cassava and sugarcane are important food sources [45]. In Sub-Saharan Africa, sorghum residue is substantially used as livestock feed and fence thatching materials. Further use of sorghum residue is as cooking fuel (firewood) in rural areas, un-utilised sorghum residues gets burnt in the field. Therefore, industrial utilisation of sweet sorghum bagasse would be a great value addition to the local farmers income. In addition to the bagasse being feedstock for bioethanol production, it can also be utilised as a biogas feedstock [22, 24]. For effective utilisation of sorghum bagasse for either bioethanol or biogas production, it must undergo certain pre-treatment processes. Firstly, the dried bagasse is crushed and milled. The milled bagasse is usually acid treated or alternatively treated with alkaline solution to disrupt the lignocellulosic matrix structure of the bagasse biomass, this helps liberate the individual cellulose and hemicellulose polysaccharides [7-9]. Afterwards, the polysaccharides are further degraded to simpler molecules e.g. monomers of glucose, maltose, xylose, arabinose via enzymatic hydrolysis. The hydrolysate is yeast fermented to ethanol. The fermentation process major by-products include carbon dioxide and vinasse slurry. Sorghum bagasse vinasse contains significant amount of nutrients that may be transformed into biogas [19-21]. Therefore, the fermentation vinasse is considered a suitable substrate for biogas production. The amount of biogas that can be generated from the vinasse largely depends on the composition of the input substrate. On the other hand, after the biogas production, the residual slurry (digestate) in the bioreactors can be used as organic fertilizer in farms either as slurry or as dried solid. All residual undigested solids from the bioreactor as well as the fermenter can be diverted to co-generation plants for heat and electricity generation[47]. Table 9 summarises the multiple feedstock that can be derived from sweet sorghum biomass.

Table 9 Sweet sorghum as multiple feedstock sources

s/no.	As crop	As ethanol source	As bagasse	As raw material for industrial product
	Short duration: 3–5 months	Amenable to eco-friendly processing	High biological value	Cost-effective source of pulp for paper making
	C4 dry land crop.	Less sulphur in ethanol	Rich in micronutrients	Dry ice, acetic acid, fusel oil and methane can be produced from the co-products of fermentation
	Good tolerance of biotic and abiotic constraints	High octane rating	Use as feed, for co-generation power plants or bio-composting	Butanol, lactic acid, acetic acid and beverages can be manufactured
	Meets food, feed & energy needs	Automobile friendly (up to 25 % of ethanol-petrol mixture without engine modification)	Good for silage Preparation.	
	Non-invasive species with Low soil N_2O and CO_2 emissions Seed propagated			

Source: Khawaja (2014).

SWEET SORGHUM CROP AND DISEASES

The productivity of sorghum crops depend on several parameters, in particular insect and microbial borne diseases. For example, sorghum grain mold (a condition that usually occurred between the crop's anthesis and physiological maturity stage) is a serious constrain for optimum grain yield[48-49]. Infection biology suggests the existence of natural intrinsic and adaptive response mechanisms in host sorghum to protect against and overcome parasitic and pathogenic attacks.

Sorghum ergot, caused by *Clavicep africana*, is pandermic/endermic and constitutes a major global threat to sorghum production. Genetic studies have identified some quantitative trait loci (QTL) associated with the conferment of ergot resistance in some sorghum cultivars[50]. While some of the QTLs appeared to be linked to two pollen traits (pollen quantity and pollen viability) located on four chromosomes, there were others that mapped elsewhere to suggest the existence of both pollen and non-pollen dependent mechanisms. Interestingly, the QTLs appeared to be influenced by environmental factors (temperature and humidity) and could be utilised as selection markers to identify or develop ergot resistance sorghum strains. The anthracnose (target leaf spot) pathogenic fungus, *Colletorichum sublineolum*, is reported to induce the secretion of phytoalexins in the form 3-deoxyanthocyanidins at the site of infection in *Sorghum bicolor*[51]. The production of the 3-deoxyanthocyanidins is via coordinate gene expression clusters and networks that include genes of the glyoxylate shunt of the TCA cycle and genes encoding amino acids metabolising enzymes[52]. These pathways also relate to glutathione (GSH) anabolism and catabolism necessary for the maintenance of cellular redox status. The phytoalexins, such as 3-deoxyanthocyanidins, are very stable antioxidants[53-55] that share structural similarity to the precursors of phlobaphenes[51]. The biosynthesis of phlobaphens is regulated by the MYB transcription factor encoded by the sorghum yellow seed1 (*y1*) gene. A functional *y1* gene appears to be required for the accumulation of 3-deoxyanthocyanidins which correlate with the resistance to *Colletorichum sublineolum* in *Sorghum bicolor*[51]. Further, a protein kinase gene (*ds1*) has recently been isolated by positional cloning and its suppression or loss of function leads to resistance to target leaf spot caused by *Bipolaris sorghicola* infection in sorghum[56]. It is conceivable that the diffusible product of the *y1* gene (MYB transcription factor) and/or its interacting partner proteins complex or the 3-deoxyanthocyanidins biosynthetic genes network is a direct or an indirect target of the *ds1* gene kinase. It is pertinent to mention that pigmented sorghum varieties contain very high levels of 3-deoxyanthocyanidins (apigeninidin and leteolinidin) and phenolic acids (benzoic acid, p-coumaric acid and o-coumaric acid)[53].

Furthermore, *Sporisorium reilianum*, which is a fungus that causes the head smut disease in sorghum and maize, induced the synthesis of epigeninidin and leteolinidin in sorghum following colonisation[57]. The induced production of these phytochemicals appeared to be partly accounted for by the transcriptional upregulation of the phytoalexin biosynthesis gene SbDFR3. It has been demonstrated *in vitro* that leteolinidin but not epigeninidin inhibited the vegetative growth of *Sporisorium reilianum*, suggesting that the regulation of leteolinidin biosynthesis determines the successful infectivity and colonisation of sorghum by *Sporisorium reilianum*[57]. The *Sporisorium reilianum* infection is much clearer at the flowering stage of the host sorghum plant, when the fungus has matured and started to form spores and phyllody in the inflorescences. Consequently, the fungus triggers damage and loss of organ and meristem identity in male inflorescences and a loss of meristem determinacy in female inflorescences and flowers in maize[58]. Transcriptional profiling by microarray analysis showed these *Sporisorium reilianum* induced developmental changes in maize to be accompanied by transcriptional (genes proposed to regulate floral organ and meristem identity), hormonal (30% increase in the level of auxins) and redox (increased accumulation of ROS) modulation[58]. This may be the case with Sorghum bicolor following colonisation by *Sporisorium reilianum*, though it is not clear whether the observed triggered changes and modulations are signatures of the host defence and adaptive responses or signatures in favour of pathogen colonisation and survival, or both. Overall, the phytoalexins and other phytochemicals from sorghum are increasingly becoming to be of great potential value to the nutraceutical and pharmaceutical industries[53-55,59-65].

Next, sorghum biomass production is also greatly hampered by insects that target various parts of the plant and at different developmental stages. Certain infestations can specifically cause loss of ears, and lodging, shattering and complete destruction of maturing stalk. There are over 150 insect species known to infest sorghum cultivars on a global scale, which undoubtedly have been adaptive selection pressures for the emergence of insect tolerant sorghum varieties. This contention is supported by genetic research findings demonstrating the existence of insect resistance genes in sorghum and the identification of insect resistant sorghum strains[66-68]. Several molecular mechanisms appeared to be evoked following such biotic stresses, for tens and hundreds of divergent genes are co-ordinately up regulated in response[66-67].

Striga hermonthica, commonly known as African witchweed, is a hemi-parasitic weed that infests cereal crops (gramineous plants) resulting in great economic losses[69-72]. Ezeaku and Gupta[69] reported that a 2001 survey found an estimated 21 million hectares of land out of the total land area dedicated for sorghum cultivation in Africa was infested with *Striga hermonthica*, resulting in an estimated annual grain yield loss of about 4.1 million tones that could translate into a cumulative revenue losses of about 7 billion US dollars to farmers. In Africa, *Striga hermonthica* was identified as the most destructive parasitic weed in the western part of the continent accounting for regional grain losses of 5–10% annually. Some hybrid cultivars cultivated in Nigeria have been identified to be resistant to *Striga* attack and they include KSV4, ICSV111, ICSV400, S-35 and Gaya early[69,73].

According to USAID[74], diseases commonly associated with sorghum crops cultivation in Nigeria may be classified as follows:

a. Diseases that affect germinating seedlings by causing retardation of seedling germination growth or death.

b. Diseases that invade leaves causing reduced biomass yield potential and photosynthesis efficiency.

c. And lastly, diseases that attack roots and stems causing root and stem rot, poor stalk juice yield and subsequently low or no grain yield.

Companion crops (e.g. intercropping sorghum with leguminous plants like groundnut, cowpea and acacia) have traditionally been used by local African farmers to check the menace of Striga infestation. The method has proved affordable, as well as valuable in providing plant nutrition, water and good soil retention, and fodder forage for farm animals[75]. It is well known that legumes fix nitrogen (N) in the soil via root nodular formations by nitrate and nitrite reducing microorganisms. However, the role of intercropping with leguminous plants is extended beyond enhancing the nutritional status and well being of the sorghum plant to withstand and overcome Striga infestation. Evidence has emerged to implicate N starvation, as well as P deficiency, in promoting the production and exudation of strigolactones by the roots of *Striga hermotheca*[76-77]. The strigolactones were first identified as highly potent germination stimulants for the seeds of Striga[76,78] and as such considered to be detrimental to the host plant producing them[79].

The strigolactones are isoprenoids belonging to sesquiterpene lactones that are of relatively unknown biosynthetic pathways[76,78]. However, using carotenoid deficient mutant plants and inhibitors of the isoprenoids pathways in wild-type plants, Matusova *et. al.*[76] have demonstrated the origin and the formation of the strigolactones to be linked to the carotenoid pathways. The sorghum root exudates contain proportionate mixture of strigolactones in the forms of 5-deoxy-strigol, sorgolactone, strigol, and lipid resorcinol analogs, as well as a number of minor sorgoleone congeners[76,78]. The strigolactones not only stimulate the germination of S. hermontheca but also induce the growth and development of arbuscular mycorrhizal (AM) fungi[78], which is a known mutualistic and symbiotic organism colonising the roots of most terrestrial plants[78]. AM fungi uptake nutrients (N & P) from the soil and exchange them for photosynthetically fixed carbon (C) from the plant host[80]. It is now becoming clear that C supply from the host regulates the fungal up-take and accumulation of

N, P, K and Cl ions) and the translocation of some of these nutrients to the host[77,80]. It is likely that the primary purpose of strigolactones from sorghum is to promote the germination, growth and development of AM fungi and to utilise and sustain the symbiotic system rather than to support the germination and establishment of *S. hermontheca*. At a later point the parasitic *S. hermontheca* was able to exploit and broker this novel symbiotic relationship to infest plant hosts like *Sorghum bicolor*. This assertion is supported by the increase recognition of strigolactones and the AM fungal rhizosphere in signalling and in plant growth and development[77,81].

Sorghum is considered one of the more allelopathic crop species, producing phytotoxins such as the potent benzoquinone sorgoleone (2-hydroxy-5-methoxy-3-[(Z,Z)-8',11',14'-pentadecatriene]-*p*-benzoquinone) and its analogs[82]. Sorgoleone typically represents the predominant constituent of *Sorghum bicolor* root exudates and likely accounts for much of the allelopathy of *Sorghum* spp. Sorgoleone, as strigolactone and as major component of the hydrophobic root exudates of sorghum, is one of the most studied allelochemicals. It is of particular interest to plant chemical ecology as well as agriculture. Sorgoleone is likely responsible for much of the allelopathic properties of sorghum root exudates against broadleaf and grass weeds. The sorgoleone lactones exudates are important signalling molecules in plants and can inhibit shoot branching. Previous studies have suggested that the biosynthetic pathway of sorgoleone lactones initiates with the synthesis of an unusual 16:3 fatty acid possessing a terminal double bond. The corresponding fatty acyl-CoA serves as a starter unit for polyketide synthases, resulting in the formation of 5-pentadecatrienyl resorcinol. This resorcinolic intermediate is then methylated by an S-adenosylmethionine-dependent O-methyltransferase and subsequently dihydroxylated to yield the reduced (hydroquinone) form of sorgoleone. The results of later studies have strongly suggested that these fatty acid de-saturates are representative of the principle enzymes involved in the biosynthesis sorgoleone[82-83]. Sorgoleone interferes with several molecular target sites, including inhibition of photosynthesis in germinating seedlings. Interestingly, sorgoleone is not trans-located acropetally in older plants, but can be absorbed through the hypocotyl and cotyledonary tissues. Suggesting the mode of action of sorgoleone may be the result of inhibition of photosynthesis in young seedlings in concert with inhibition of its other molecular target sites in older plants[83].

Recent work has demonstrated that the integration of sorghum bicolor root plant water extracts, as naturally occurring allopathic phytotoxins, help reduced herbicide dose or rates and provide effective weed control and a wheat yield comparable to using the recommended herbicide dose[83-84]. Sorgoleone is strongly absorbed in soil that increases its persistence, because of its hydrophobic nature. Since sorgoleone is released into soil, understanding the fate of sorgoleone in soil is essential if it is to be utilized as environmentally friendly and sustainable herbicide. Sorgoleone appeared to be mineralized in soils by microorganisms, which use sorgoleone as a source of energy over time[83]. The methoxy group of sorgoleone appeared readily mineralized, whereas mineralization of the remaining molecule was slower.

Biosynthesis and exudation sorgoleones and their metabolites from Sorghum appeared to follow distinct temporal and perhaps spatial patterns, which can be induced by biotic and abiotic factors. The present state of knowledge suggests that allelopathy involves fluctuating mixtures of allelochemicals like sorgoleones and their metabolites as regulated by genotype and developmental stage of the Sorghum plant, environment, cultivation and signalling effects, as well as the chemical or microbial turnover of compounds in the soil and rhizosphere. Functional genomics is being applied to identify genes involved in biosynthesis of several identified allelochemicals from *Sorghum bicolor,* providing the potential to improve allelopathy by molecular breeding and by cross/mix cultivation with other crops. The dynamics of Sorghum crop allelopathy, inducible processes and plant signalling is gaining growing attention; however, future research should also consider allelochemical (e.g. sorgoleone) release mechanisms, persistence, selectivity and modes of action, as well as consequences of improved crop allelopathy on Sorghum plant physiology, the environment and management strategies. Development of weed-suppressive Sorghum cultivars with improved allelochemical production and selective allelopathic interference capacity is still a tempting and promising challenge, but traditional or conventional plant breeding and emerging biotechnology should be supported, allowed to thrive and pave the way.

Consequently, despite the adaptability of sorghum to stressful environmental conditions, pest and fungi attack prevention and control during crop cultivation is necessary[85-86], particularly to prevent disease infestation caused by *Striga hermonthica*, aphids, midge, stem borer etc[87-89]. Nevertheless, good cultivation management practices could effectively help reduce or eliminate disease attack incidence during sorghum cultivation. For example, proper seedling treatment prior to planting may reduce chances of seed rot and improved germination, crop rotation and inter-cropping may also reduce the possibility of spreading previous seasons disease to newly cultivating crops[75,90-92]. Various sorghum crop cultivation management practices aimed at production of sorghum biomass with improved nutrient value for healthy food and livestock feed have been published[93-95]. Although sorghum is well adapted to adverse climatic conditions, high productivity output remains constrained by poor soil quality, low and erratic rainfall and low agro-chemical inputs during cultivation. This concern is even more evident in sub-Saharan Africa and other developing countries where agro-chemicals and irrigation cultivation costs are beyond the reach of peasant farmers[96-97].

CONCLUSION

Sweet sorghum is a water efficient crop that tolerates wide ranges of biotic and abiotic stress factors. It is gown worldwide and Sub-Saharan Africa accounts for over one-third of the global production. Sweet sorghum crop is grown primarily for food, fuel and feed production. The grain is an important staple food source for millions of people in Africa, the crop has potential that can be harnessed to combat or avert hunger prevalent in some parts of the region. Regular consumption of sorghum starch can also help address some health challenges. Further, sweet sorghum crop has versatile industrial applications ranging from beverages such as in brewing, malting, ethanol fermentation, bagasse utilisation for co-generation in heat and power production, biogas generation among others. Therefore, Sub-Saharan Africa can leverage sweet sorghum's varied environmental and climatic adaptability to contribute towards climate change mitigation by growing this feedstock source for renewable energy development, drive industrial growth and address food security issues. To achieve these benefits, the need for sustained investment on research and development on improved sorghum varieties cannot be overemphasized.

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